NASA 9-Point LDI Code Validation Experiment

Yolanda R. Hicks, Robert C. Anderson, and Randy J. Locke

Abstract

This presentation highlights the experimental work to date to obtain validation data using a 9-point lean direct injector (LDI) in support of the National Combustion Code. The LDI is designed to supply fuel lean, Jet-A and air directly into the combustor such that the liquid fuel atomizes and mixes rapidly to produce short flame zones and produce low levels of oxides of nitrogen and CO. We present NO_x and CO emission results from gas sample data that support that aspect of the design concept. We describe this injector and show high speed movies of selected operating points. We present image-based species maps of OH, fuel, CH and NO obtained using planar laser induced fluorescence and chemiluminescence. We also present preliminary 2-component—axial and vertical—velocity vectors of the air flow obtained using particle image velocimetry and of the fuel drops in a combusting case. For the same combusting case, we show preliminary 3-component velocity vectors obtained using a phase Doppler anemometer. For the fueled, combusting cases especially, we found optical density is a technical concern that must be addressed, but that in general, these preliminary results are promising. All optical-based results confirm that this injector produces short flames, typically on the order of 5- to-7-mm long at typical cruise and high power engine cycle conditions.

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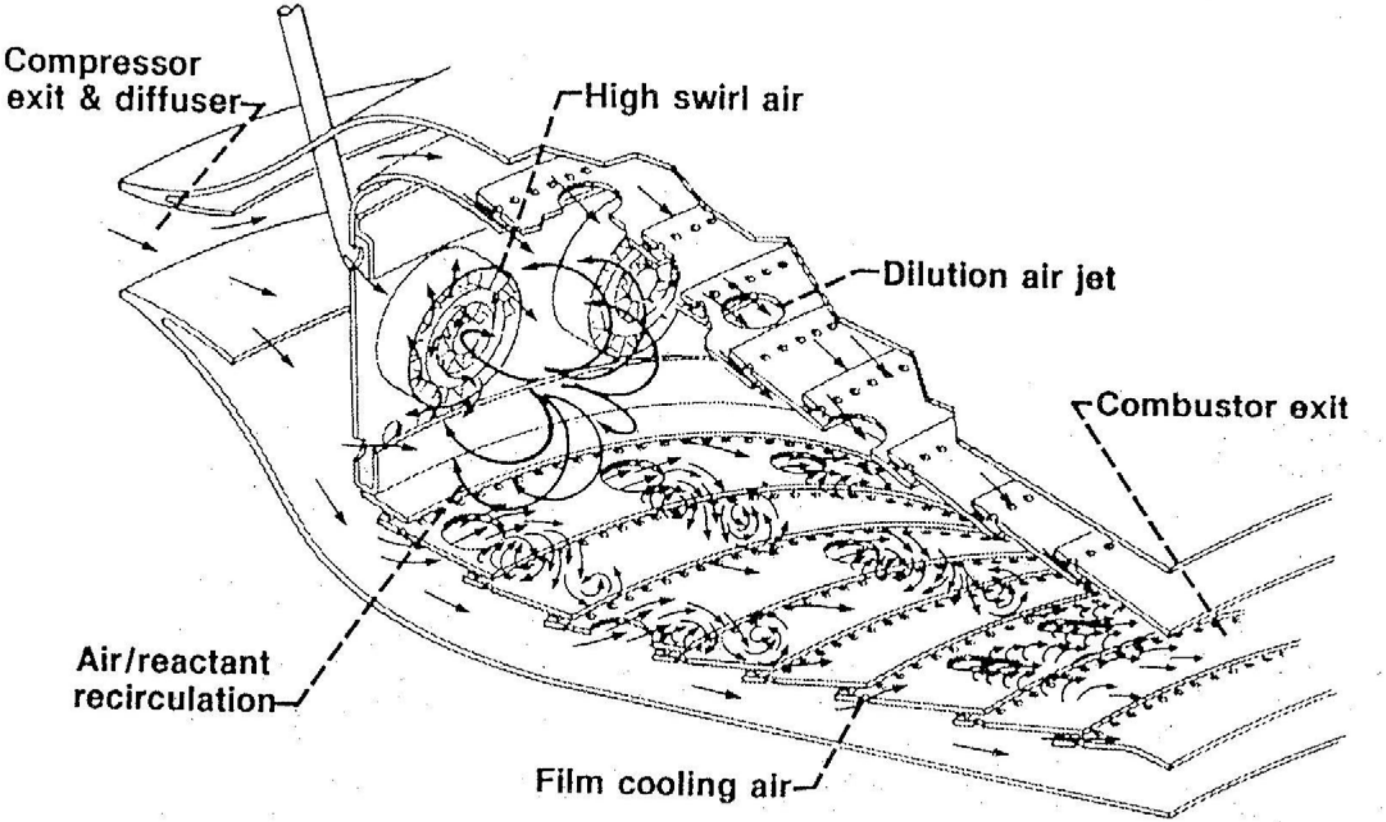
Motivation

NASA GRC has initiated efforts to develop a broad measurement database to characterize an LDI injector to facilitate understanding of the fuel vaporization, turbulent mixing and combustion processes.



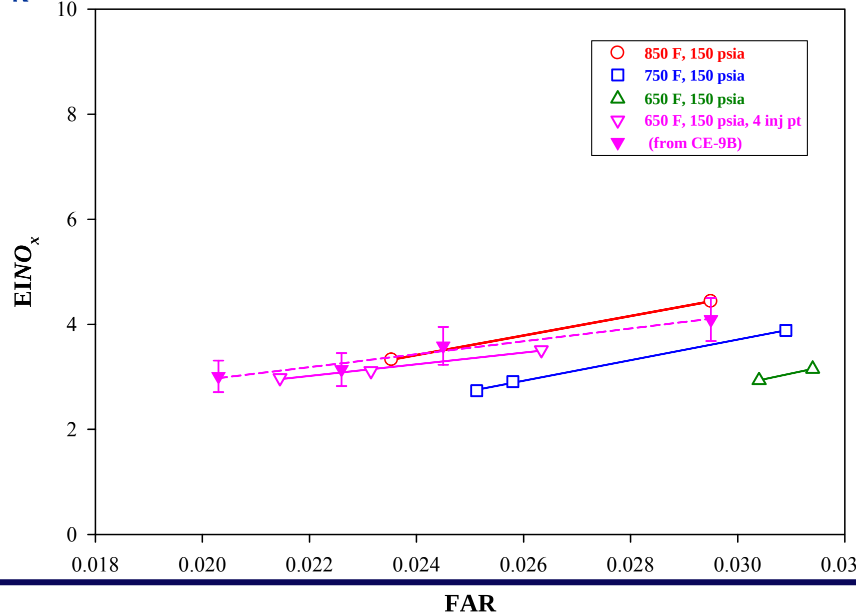
- FULLY 3-DIMENSIONAL FLOW
- HIGH TURBULENCE LEVELS
- CHEMICAL REACTION/HEAT RELEASE
- 2 PHASE WITH VAPORIZATION

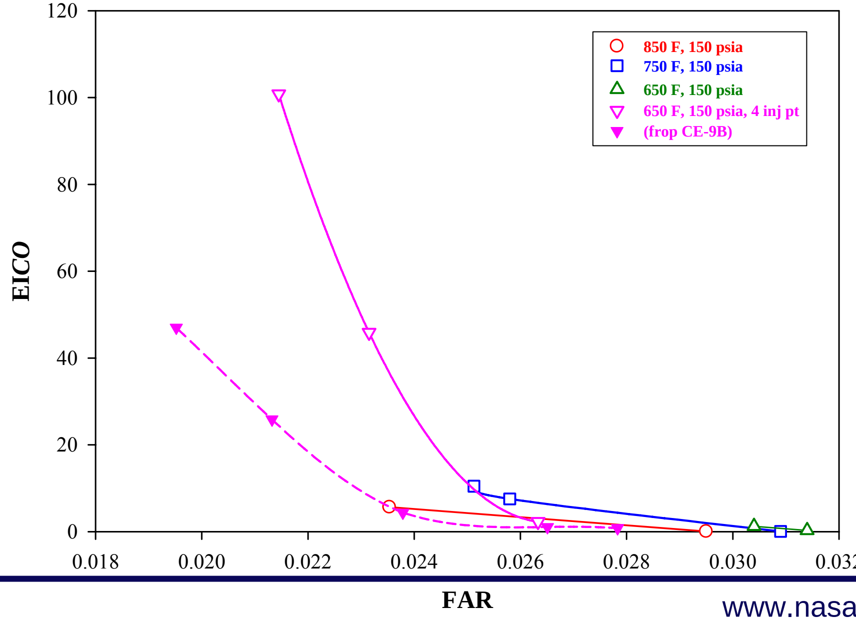
Motivation

The 9-point LDI injector will serve as a realistic test bed for validation of the NASA National Combustion Code (NCC). Advanced optical and laser diagnostic methods will be used to measure an assortment of parameters.

LDI has over a 10-year history of use at NASA GRC, in several configurations. The LDI concept has been demonstrated to reduce NOx emissions (meeting 1996 Int'l Civil Aviation Organization standards) while maintaining CO and UHC's at current levels

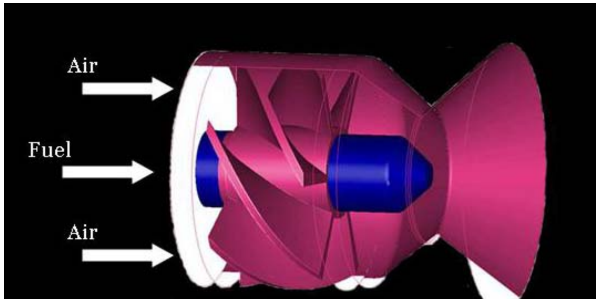
NO_x, CO emissions as a function of fuel/air ratio (FAR) and inlet temperature for the 9-pt LDI



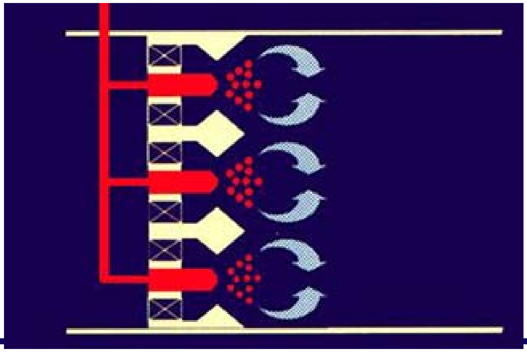


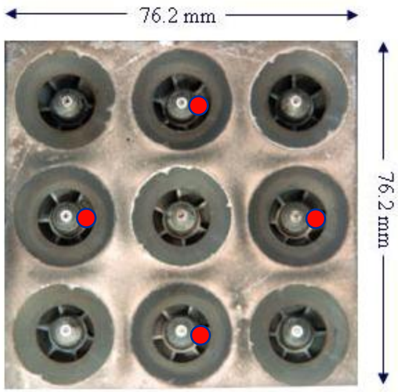
Lean Direct Injection (LDI) Basics

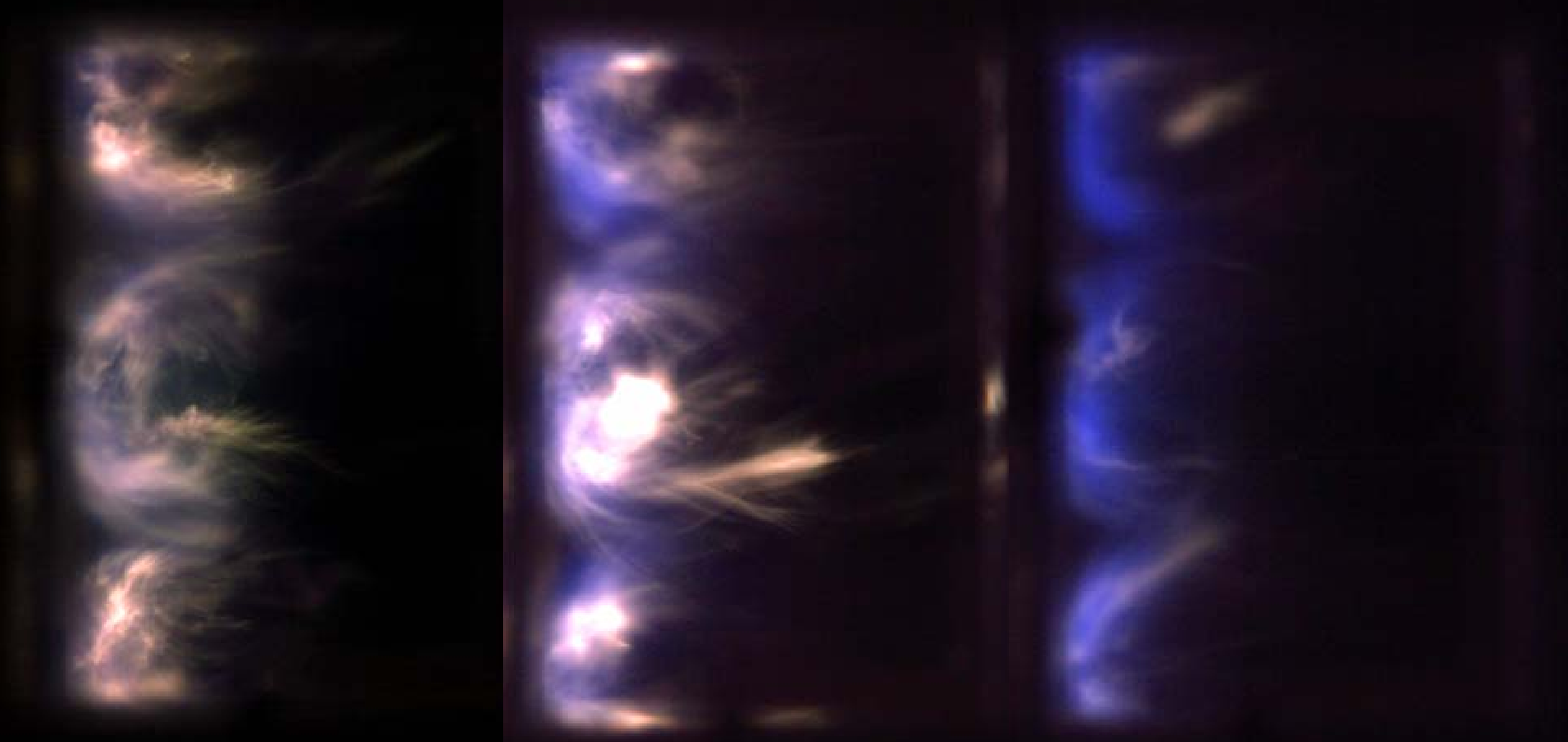
- Our LDI design is a multiplex fuel injector module containing multiple fuel injection tips and multi-burning zones and is designed to replace one conventional fuel injector
- The LDI rapidly mixes jet fuel and air thereby shortening distance to complete combustion process
- Each LDI element consist of an air passage with an upstream air swirler and a converging diverging venturi section. The simplex fuel injector is inserted through the center of the swirler and the fuel tip is at the throat of the venturi.
- Axial swirlers, helical vanes generate air swirl for quick mixing and to anchor the flame near the injector exits
- LDI allows for a variety a fuel staging possibilities



Individual LDI Injector Element



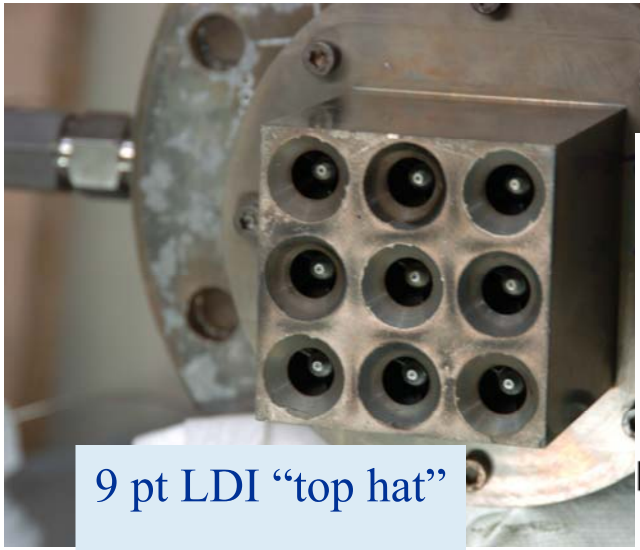




T_3 = 617 K T_3 = 728 K T_3 = 828 K

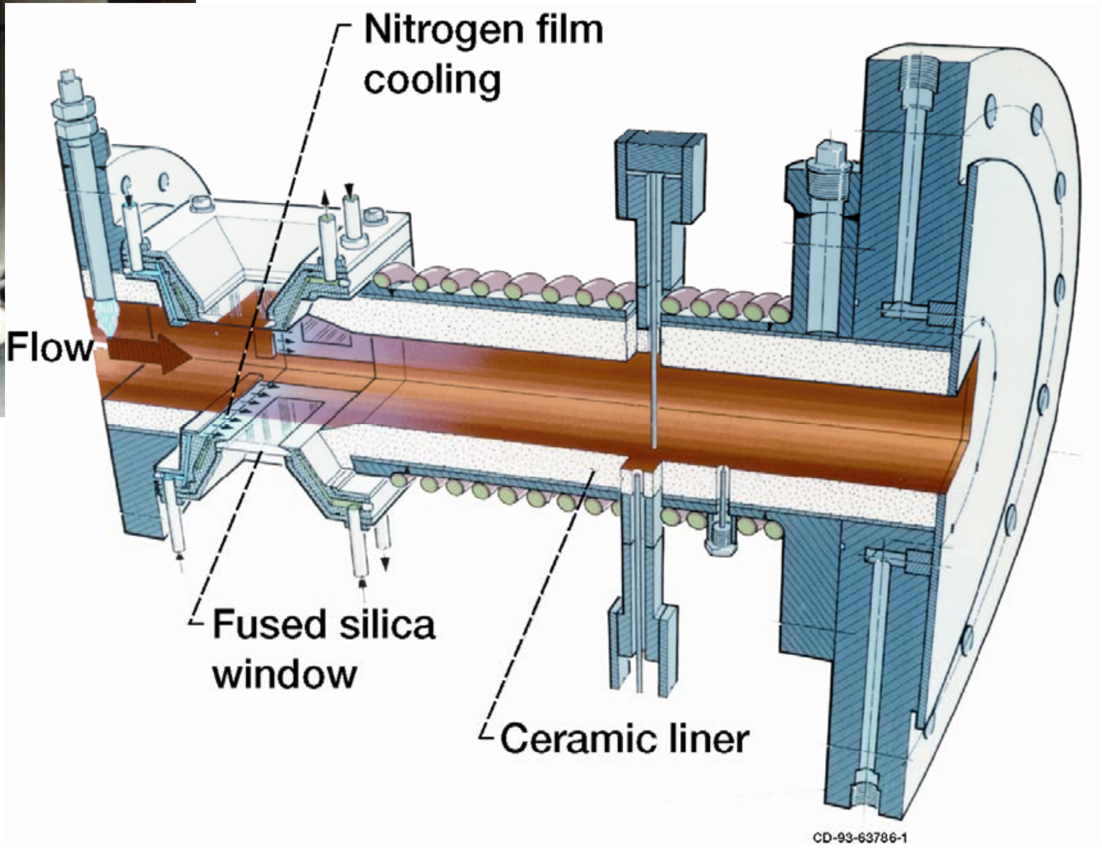
Frames from high speed movies show a turbulent, unsteady system from which flamelets can be seen. Flow is left to right.

The Hardware



9 pt LDI “top hat”

Optically-accessible flame tube



Experimental Conditions

- Inlet Pressure: 1.03 MPa (150 psia) – 1.72 MPa (250 psia)
- Inlet Temperature: 505 K (450 °F) – 827 K (1030 °F)
- $\Delta P/P$: 3-5 %
- W_{air} : 0.40 kg/s – 0.78 kg/s (0.89 – 1.71 lb_m/s)
- Φ : 0.33 – 0.55
- Fuel staging of primary (four injection elements ◇) and secondary (five elements ×) fuel circuits

Optical Diagnostics Measurement Suite

Species, temp using PLIF, light scatter or Raman scatter

- 2D, 3D mapping of: OH, NO, fuel liquid and vapor
  CH, C_2, profile and pattern factor
- 1D mapping of major combustion species:
  CO_2, O_2, N_2, hydrocarbons, H_2O

Species via chemiluminescence Imaging of C_2, CH, OH, NO

Velocity

- 2 component mapping via images—PIV
- 3 component pointwise—LDV

Drop Sizing

- 3 component pointwise—PDI
- shadowgraph-based, long range microscope

Flow/flame visualizations

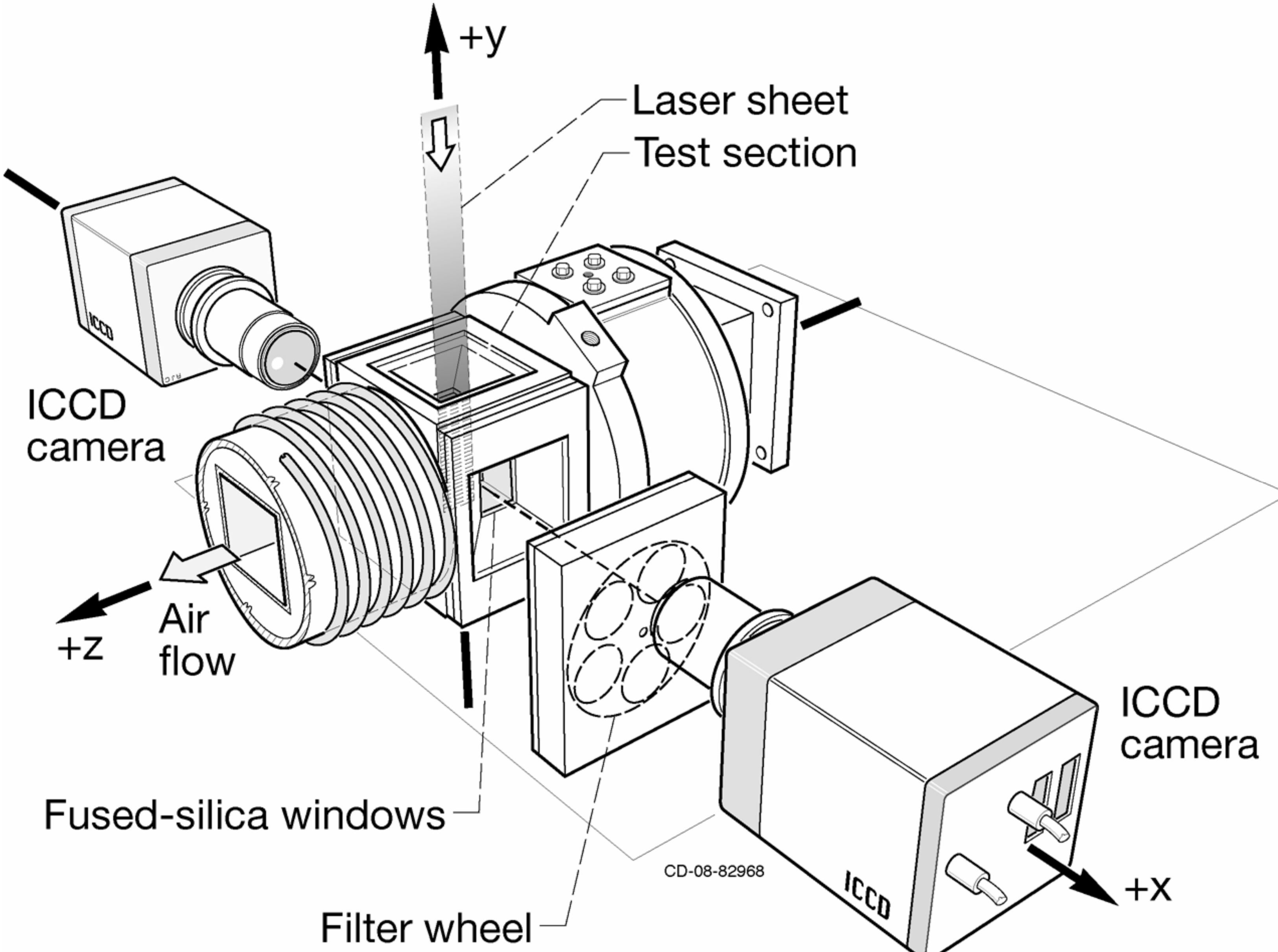
movies: video, high speed photography, schlieren, compilations of single-shot species, or of averaged data

Data acquisition and analysis

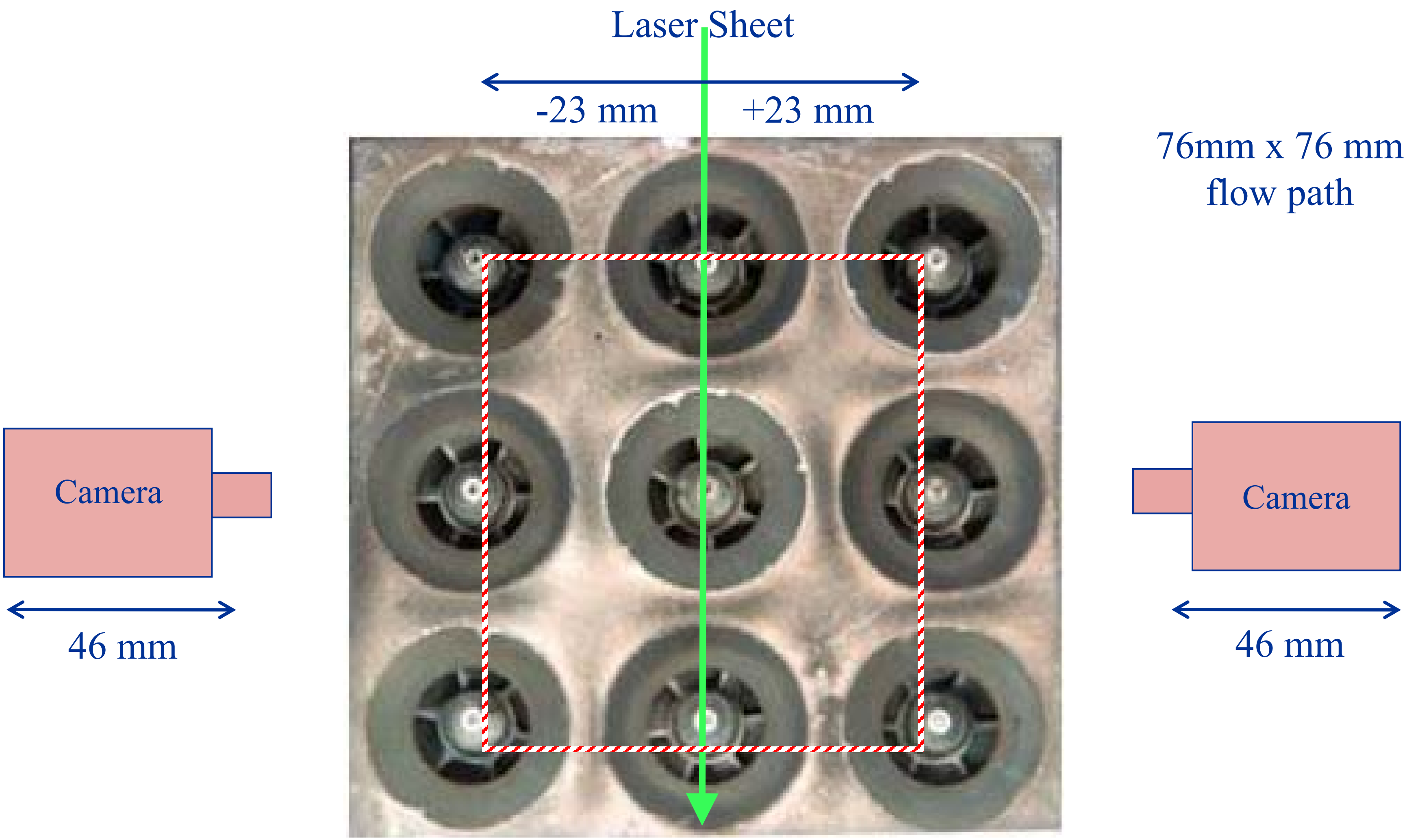
- PLIF, PLS: 10 Hz repetition rate, 100 or 200-gate on-chip avg

  Traverse in 1-mm increments from -23 to +23
- Chemiluminescence images: on-chip 200 or 600 gates
- Laser-based images subtract the appropriate background signal. Chemiluminescence images subtract minimum signal
- High Speed video photography, 16 - 19 kHz frame rate
- Air velocity: Axial-vertical maps via PIV
- Fuel drop velocity: Axial-vertical maps via PIV and 3D maps via Laser Doppler Anemometry

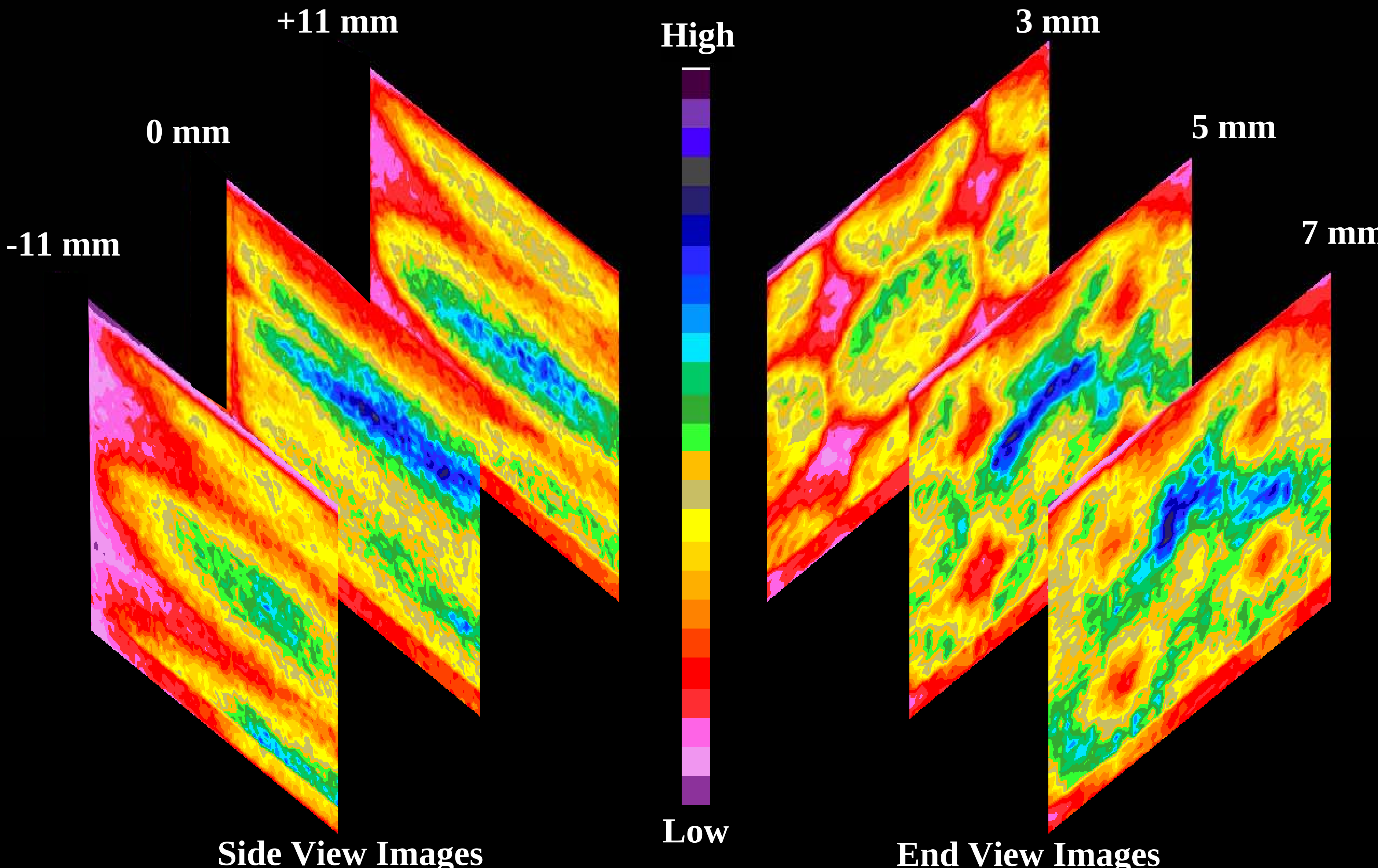
Imaging Setup



Field of view and camera arrangement for PLIF, PLS, and PIV



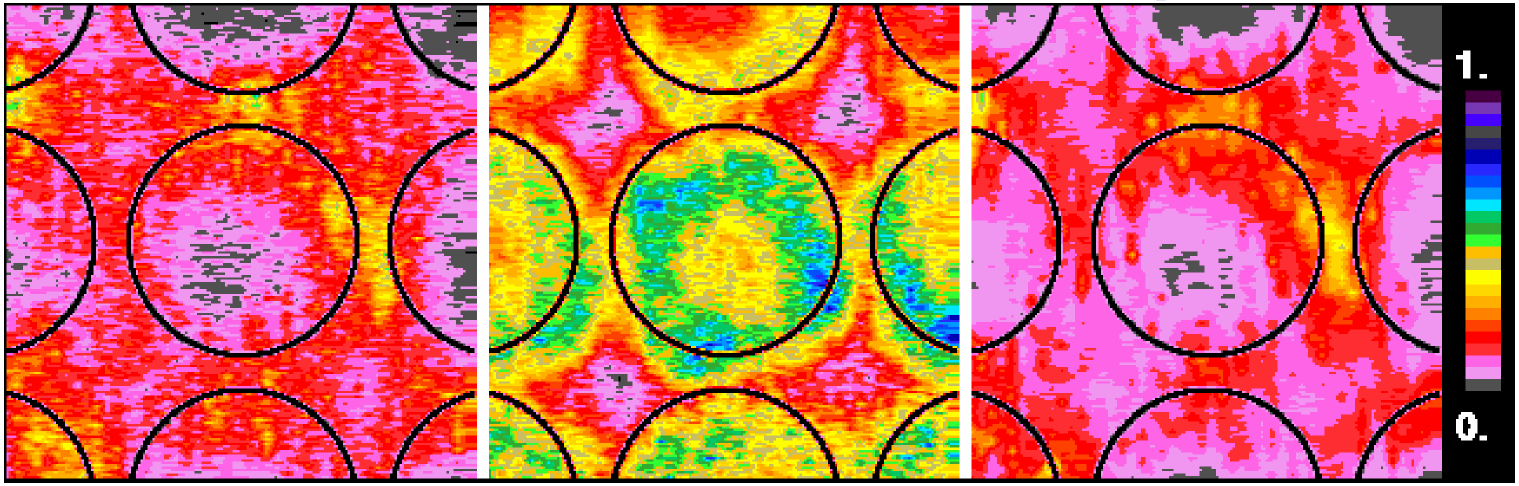
Data obtained in vertical-axial plane: **side views**



Laser-Induced Fluorescence or Scattering Data

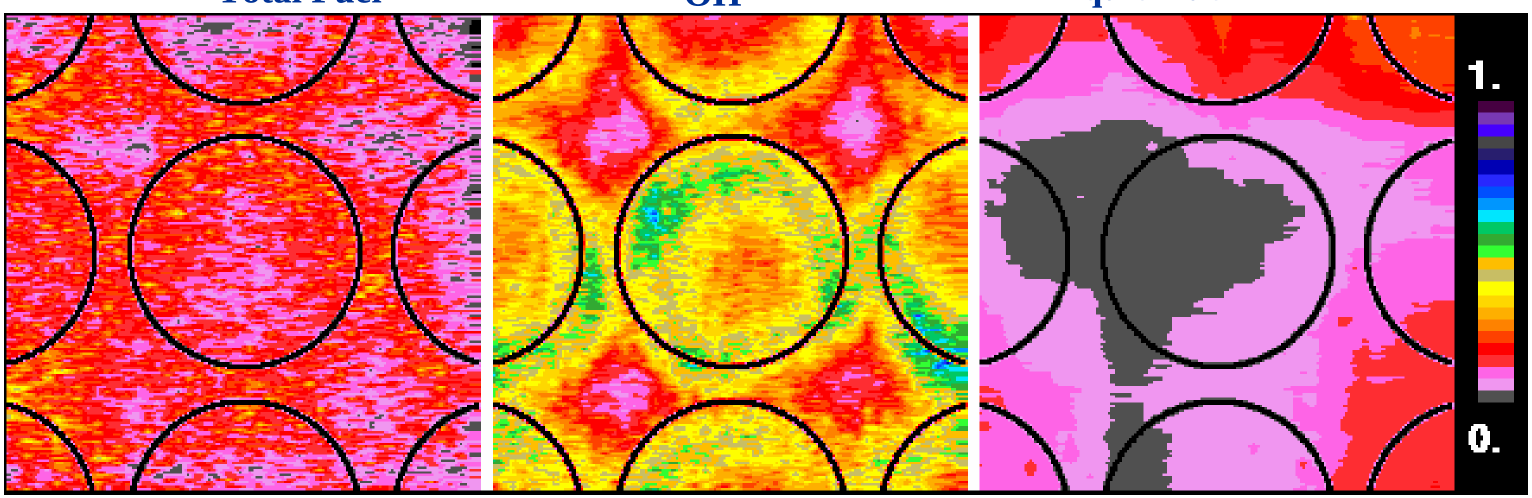
End View Composites 7.5 mm from the Injector Exit

Total Fuel **OH** **Liquid Fuel**



Inlet conditions: T = 617K, P = 1030 kPa, ϕ = 0.38, equal fuel split. "low" power

Total Fuel **OH** **Liquid Fuel**



Inlet conditions: T = 822K, P = 1723 kPa, ϕ = 0.41, equal fuel split. "high" power

Scaled per species for entire set of inlet conditions tested

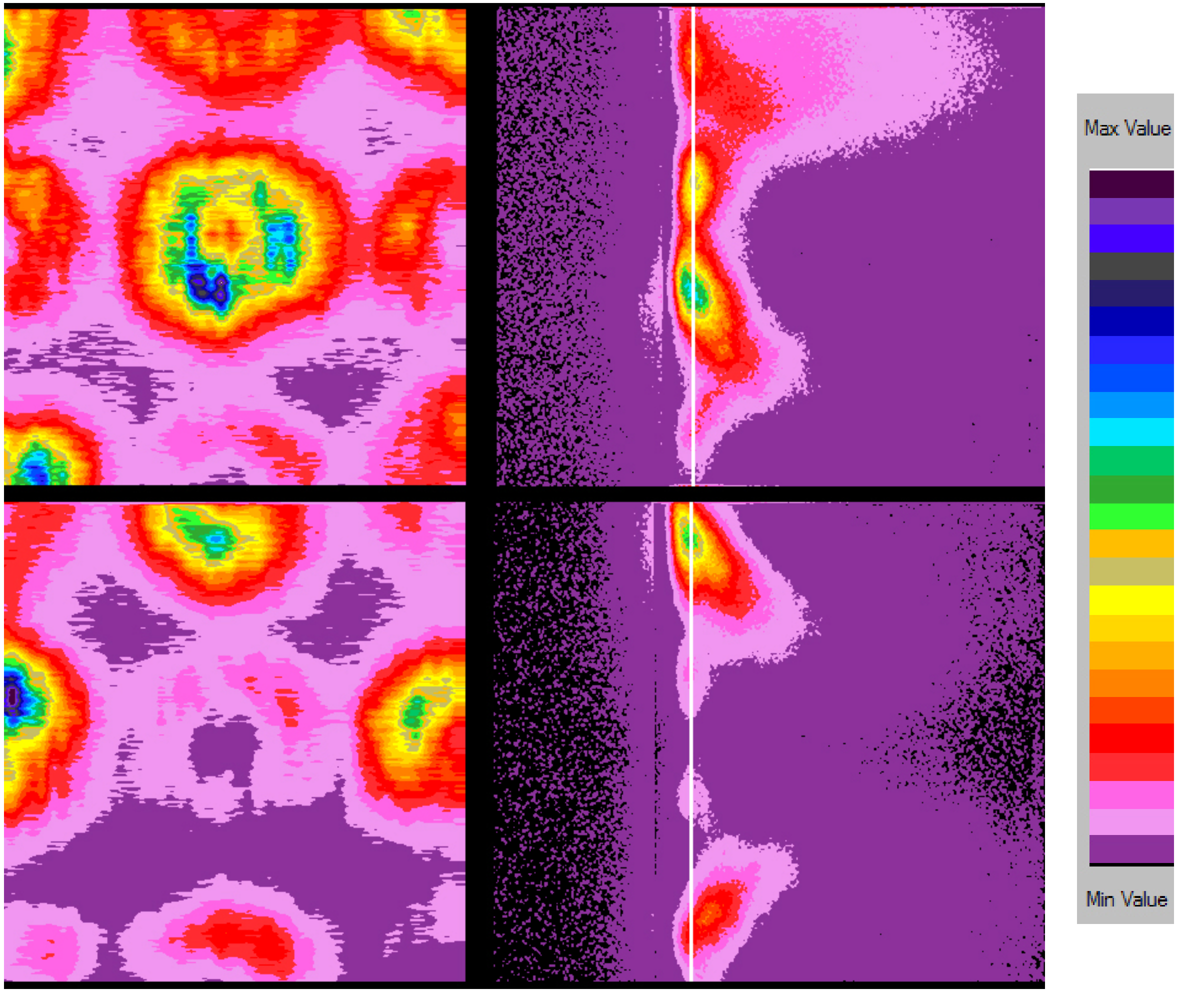
Fuel Split differences observed using fuel (via naphthalenes) PLIF

Preliminary results-uncorrected data

T_{in}= 650 F, P_{in}=150 psia

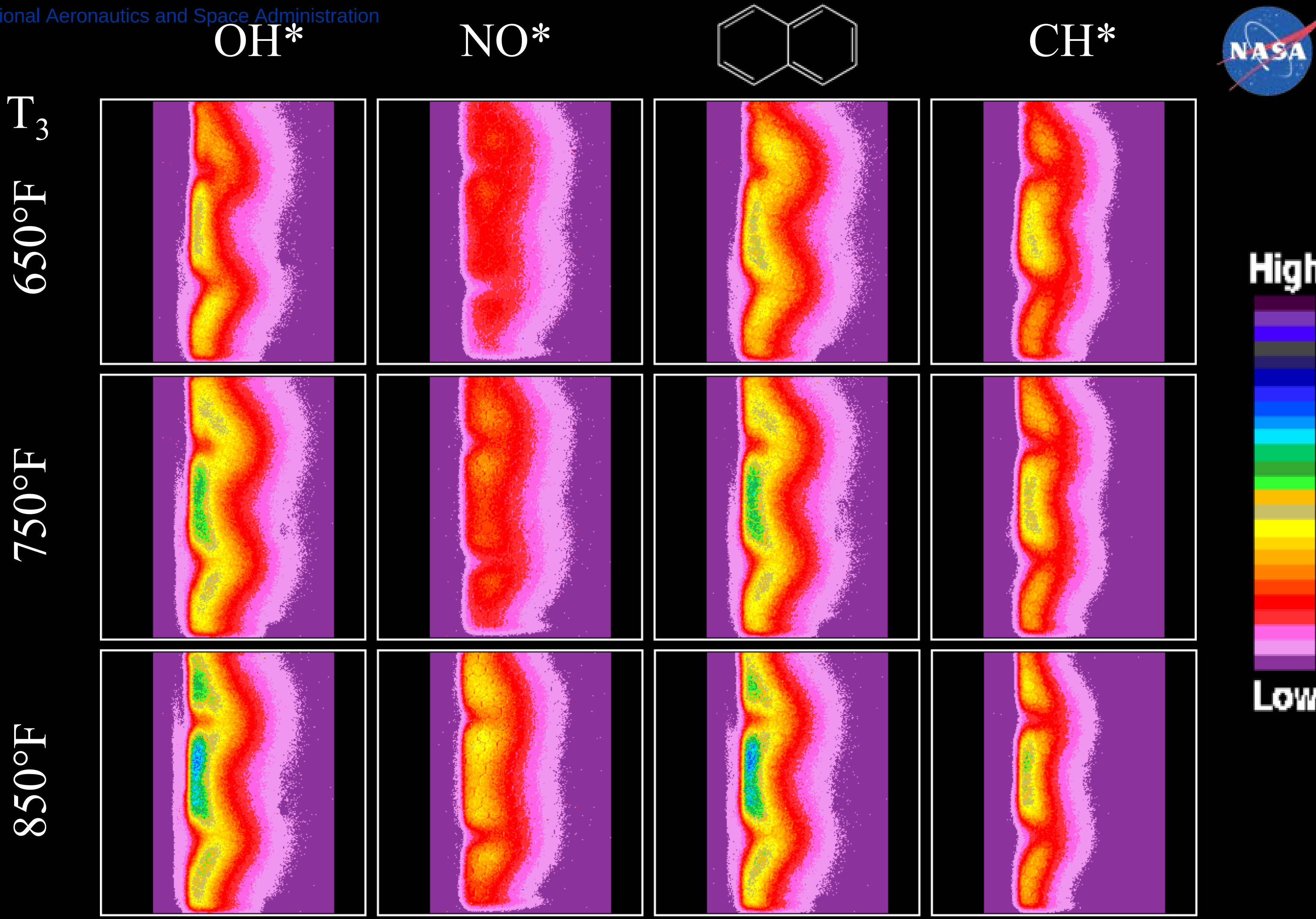
$\phi_{pry} = 0.38$
$\phi_{2ndry} = 0.38$

$\phi_{pry} = 0.65$
$\phi_{2ndry} = 0.22$



End view
3.6 mm downstream

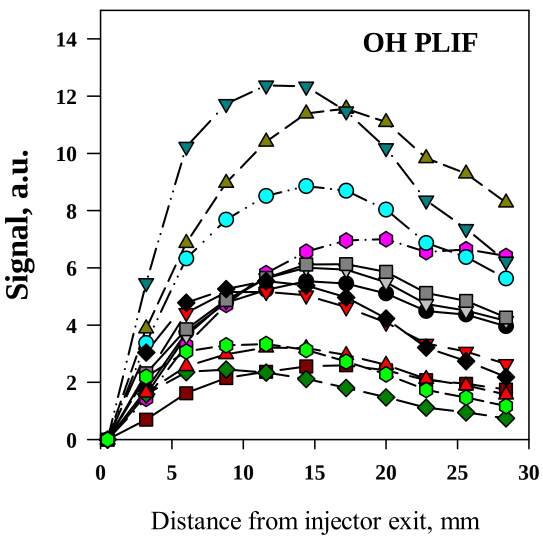
Side view in center position
White bar denotes position of end on view

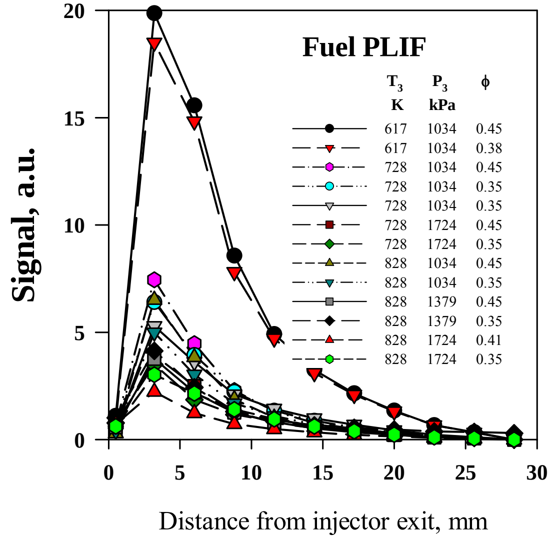


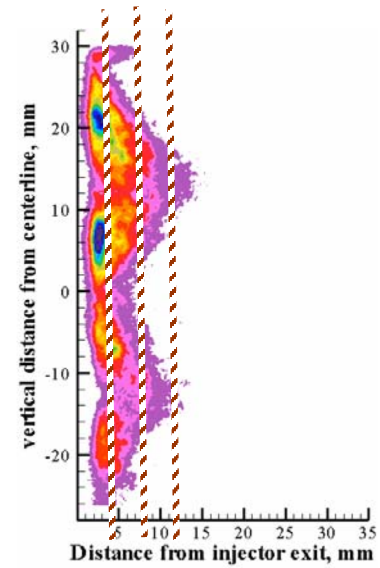
Chemiluminescence images: P_3 = 150 psia, ϕ = 0.45, even split, fuel flow normalized

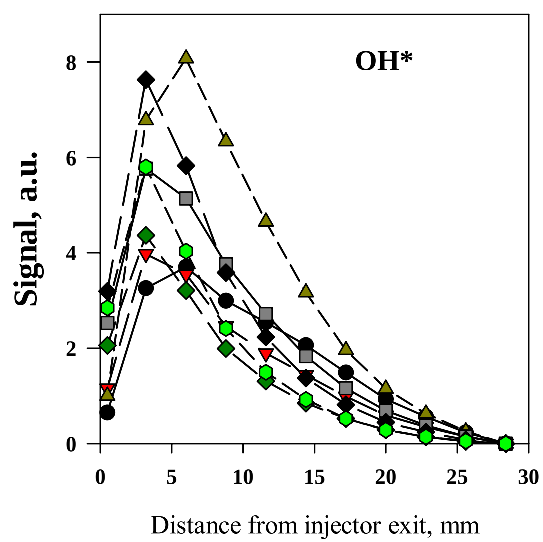
Useful for assessing overall symmetry

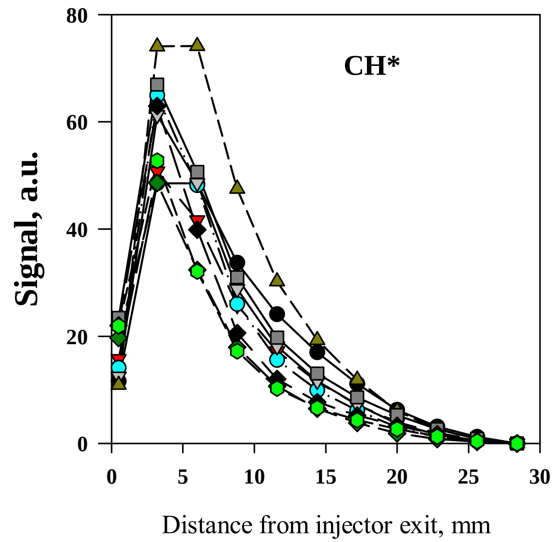
Total signal within 0.3-mm-long “probe” of data block vs. axial position











CH*, Fuel PLIF similar

OH* strong in primary reaction zone

OH PLIF: both primary/secondary rxns

Short flame zones ~ 3-8 mm from dome (except lowest inlet temperature)

Fuel flow normalized

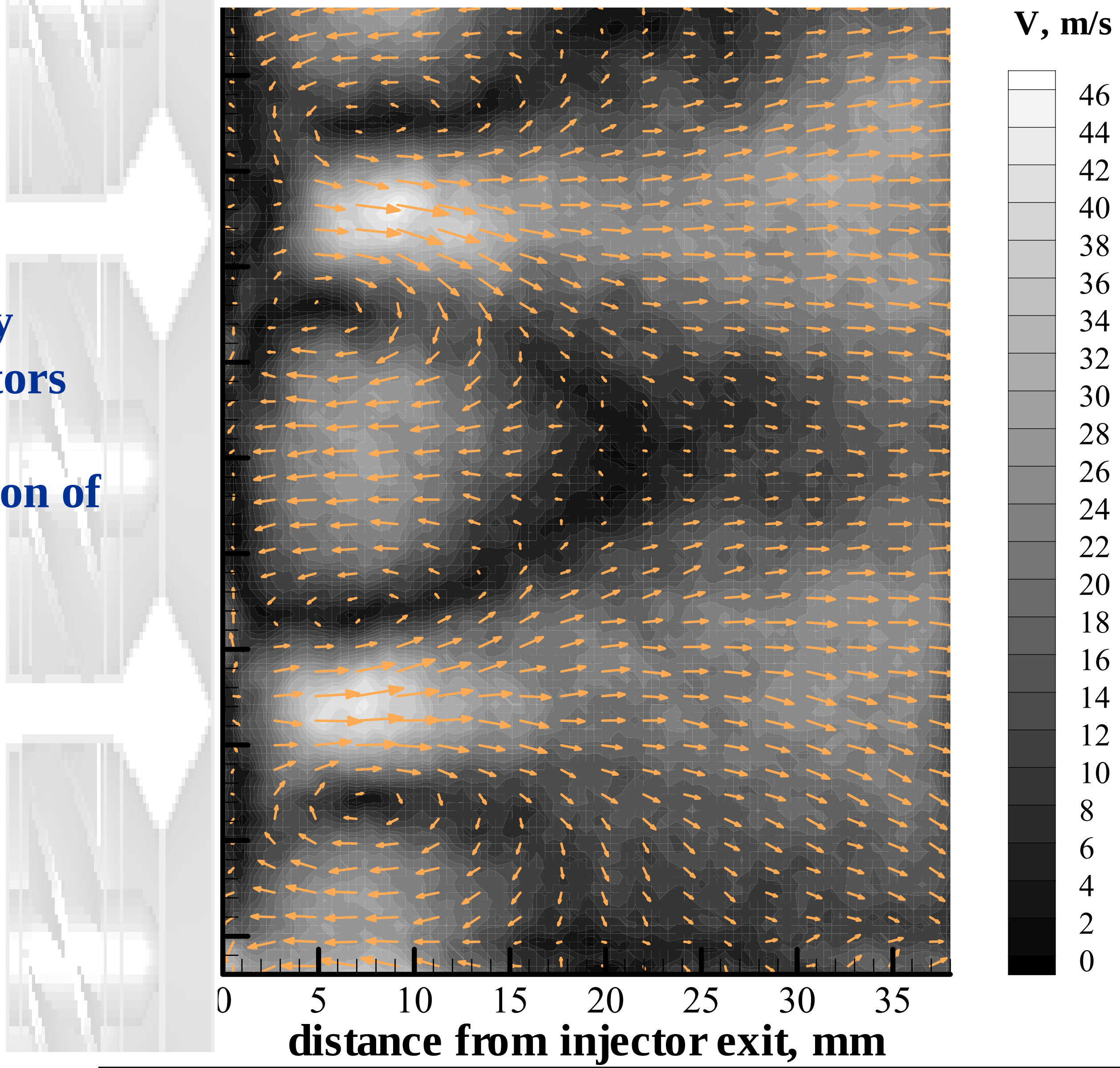
Velocity Example 1. Air only preliminary results

- Served to test of our powder seeder for elevated pressure
- Air seeded with 0.3-μm alumina particles to scatter laser
- Air velocity for axial and vertical components
- Average velocity field resultant from 200 instantaneous velocity fields
- Traverse in ~ 3-mm increments
- Experiment inlet: T_{in} = 617 K, P_{in} = 1030 kPa
- Note: Flow and model conditions are different. Physical model is slightly different than actual hardware.

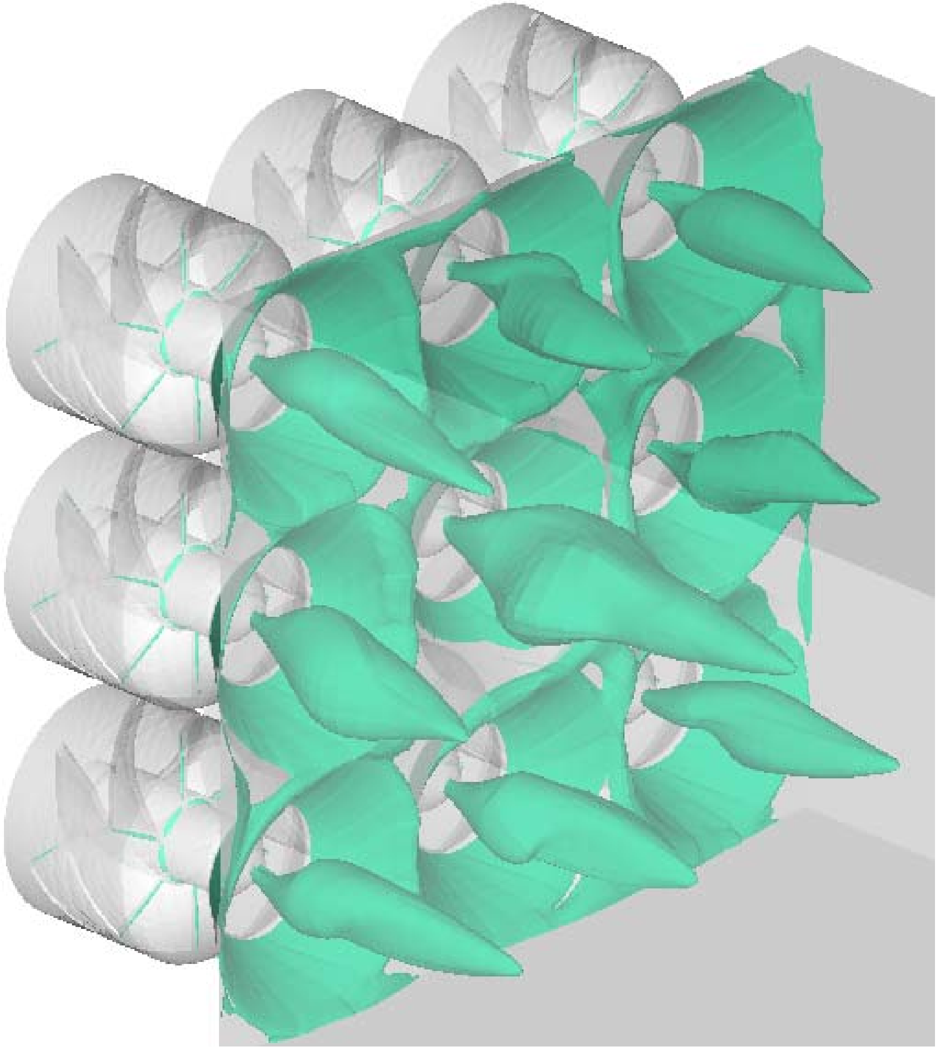
Axial and Vertical Velocity Components in the Central Vertical Plane

Recirc zones directly Dwnstream of injectors

Black bands—location of zero velocity



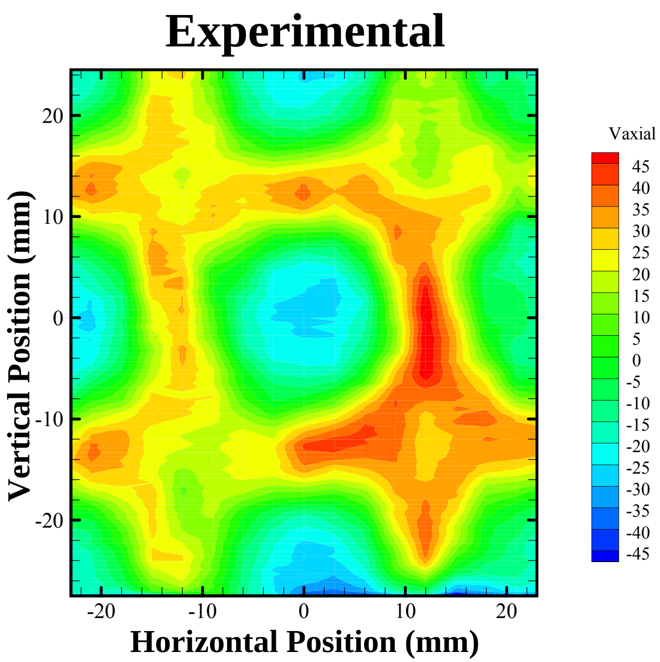
Iso-surface of zero axial velocity showing the recirculation zones



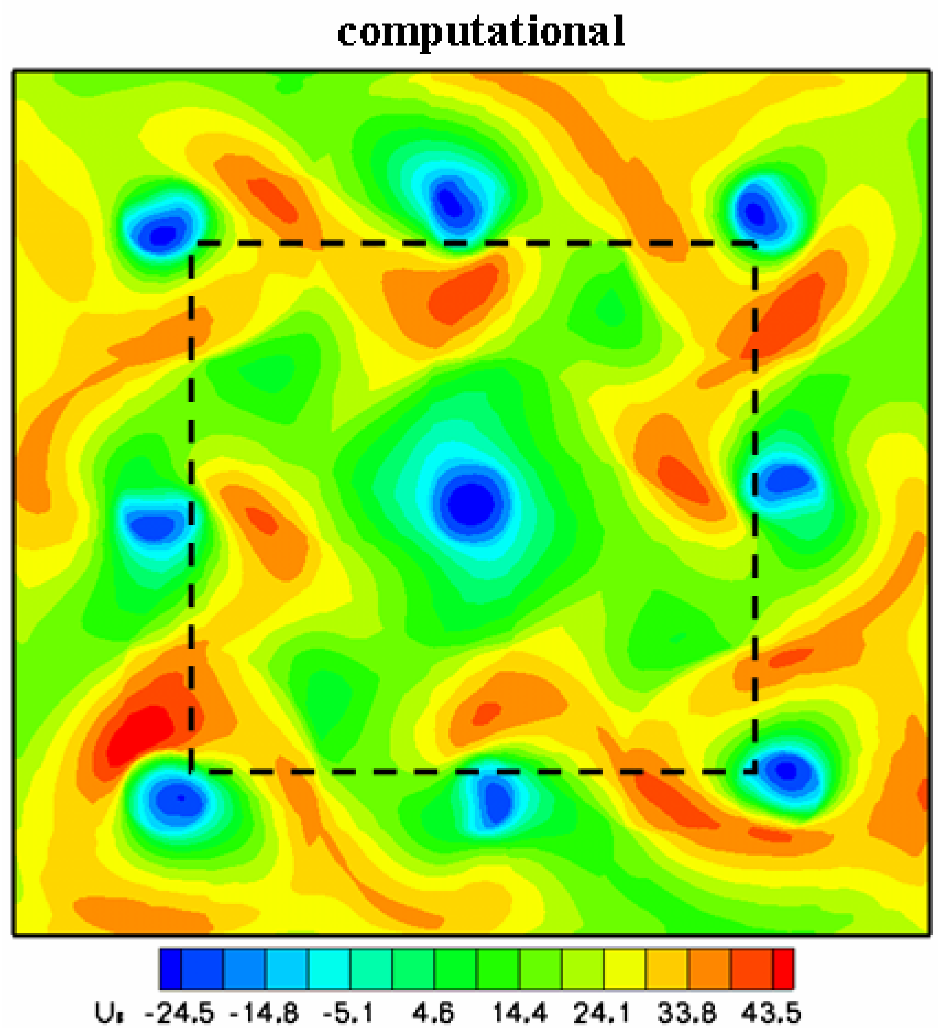
From NCC, using Reynolds-Averaged Navier Stokes Simulation

Comparison of Experimental and Computational Axial Air Velocities 6 mm Downstream of the Injector Exit Plane

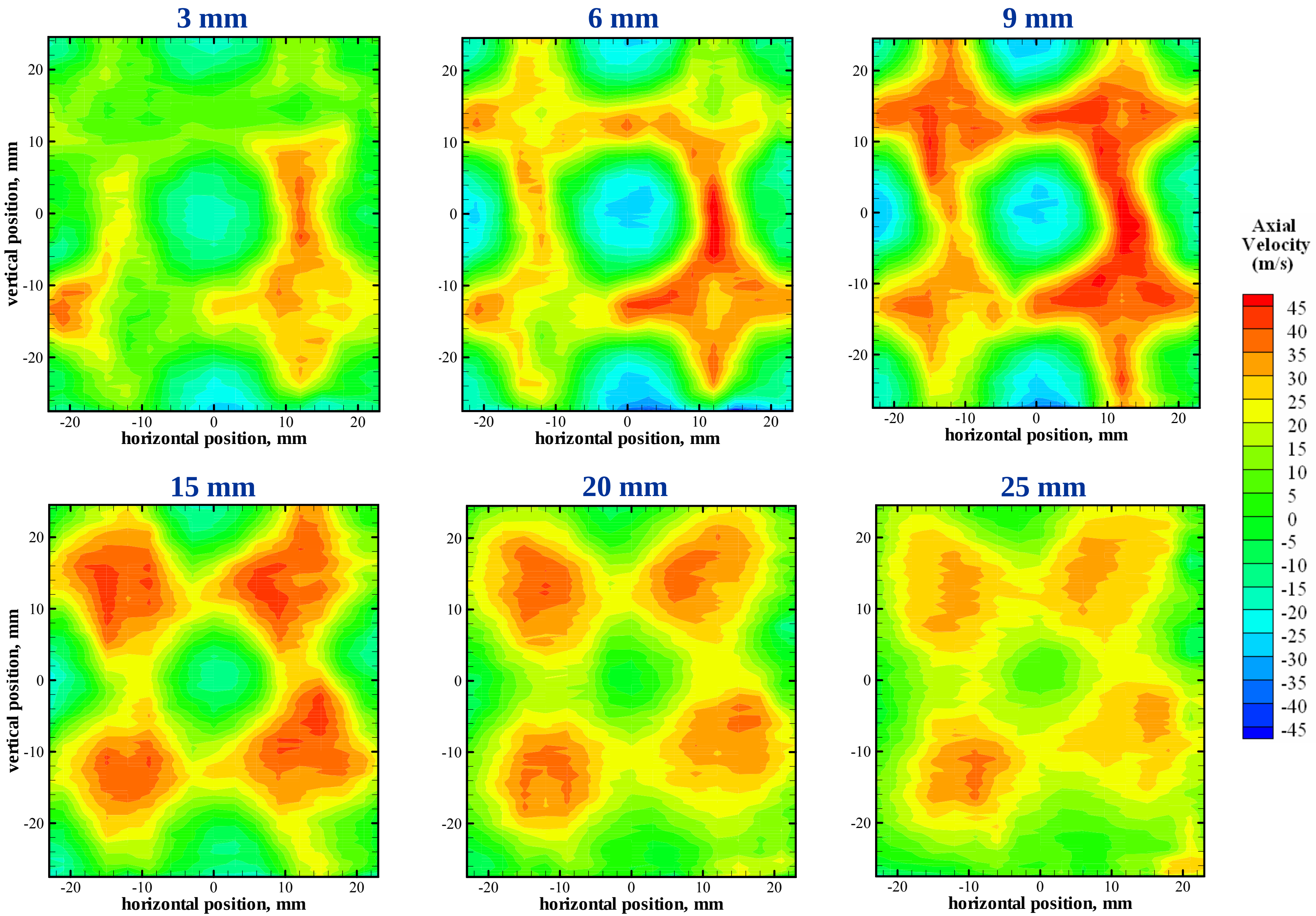
Experimental inlet conditions
T_{in} = 617K, P_{in} = 1030 kPa



Computational inlet conditions
T_{in} = 822K, P_{in} = 2740 kPa

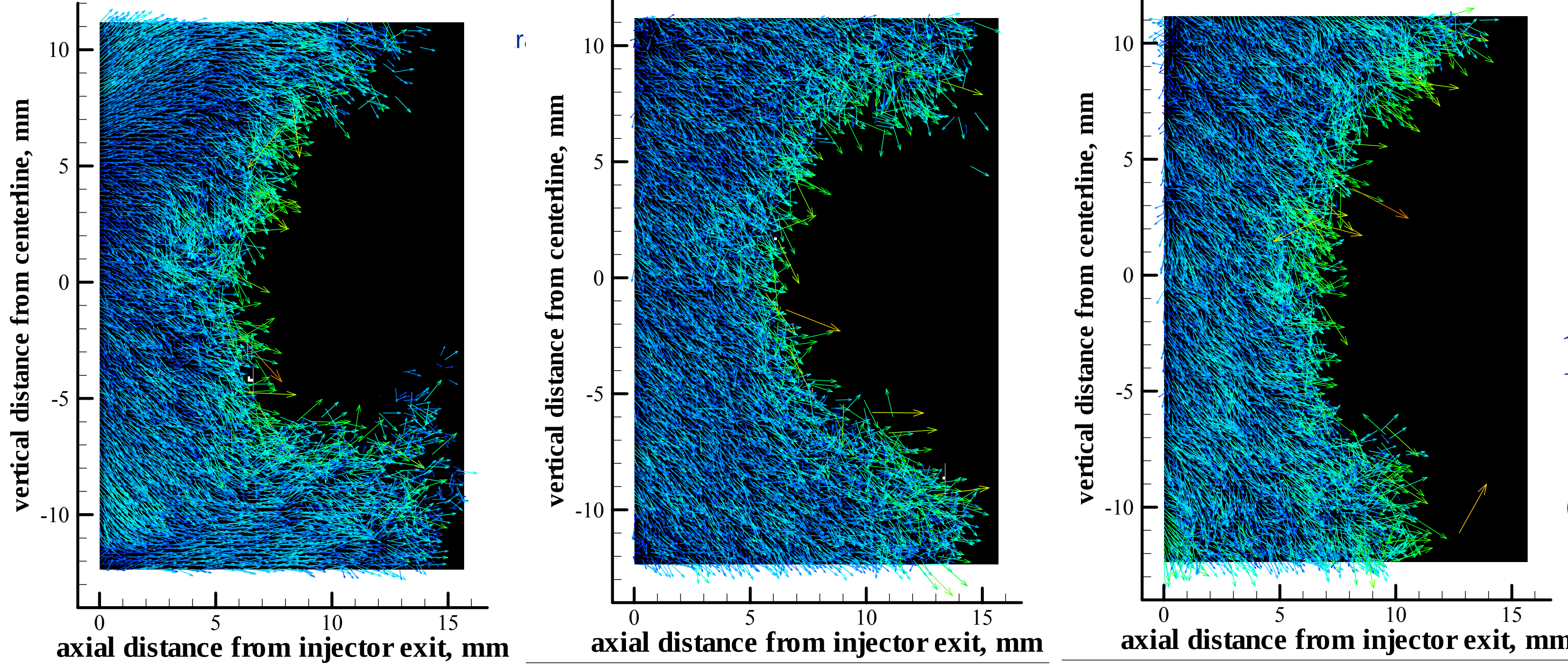


End view axial velocity contours from 3mm - 25 mm downstream from the injector exit plane. Inlet conditions: T_{in} = 617K, P_{in} = 1030 kPa.

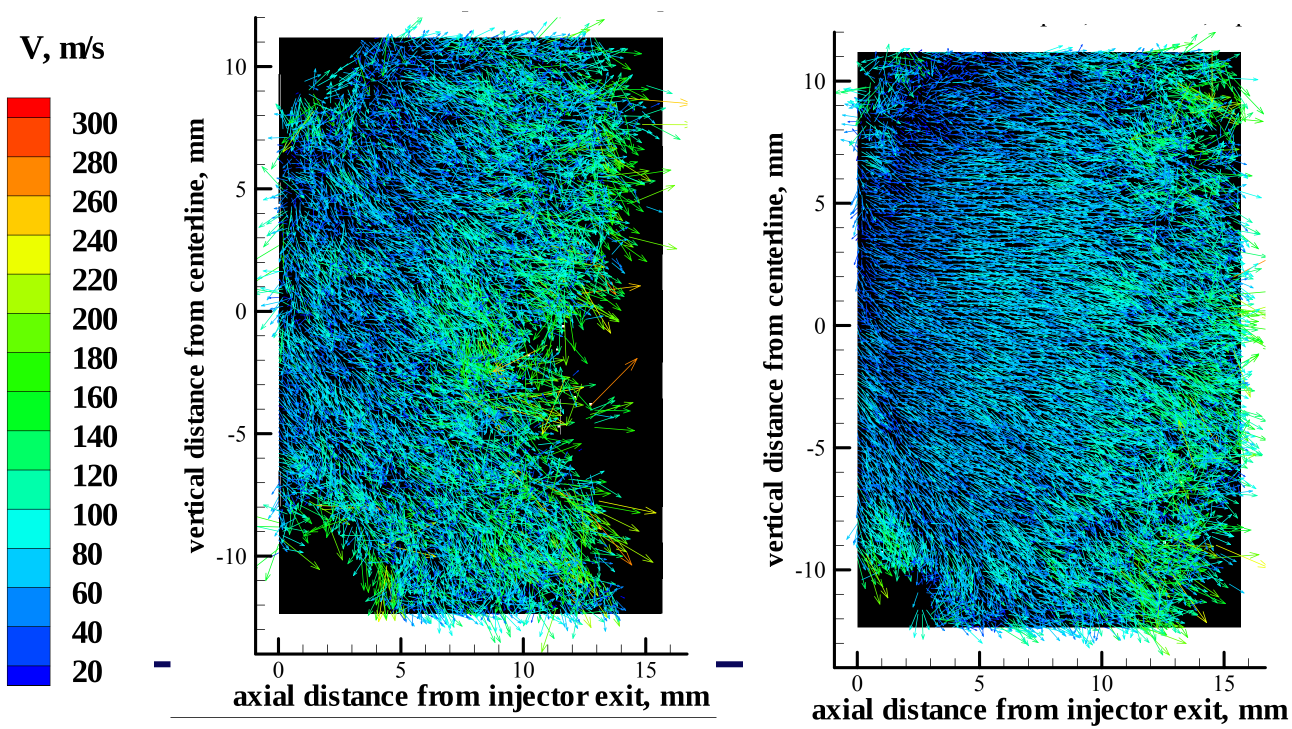


Velocity Examples 2. Fuel drops only (highly preliminary results)

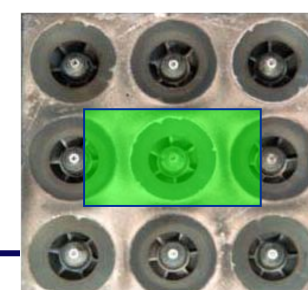
- Unseeded system, combusting environment
- P_3 = 150 psia, T_3 = 650°F, ϕ = 0.45, even fuel split
- Our first PIV measurements in a combusting system allowed us to assess shutter and timing
- Implementation issues must be resolved for PIV and LDV measurement techniques



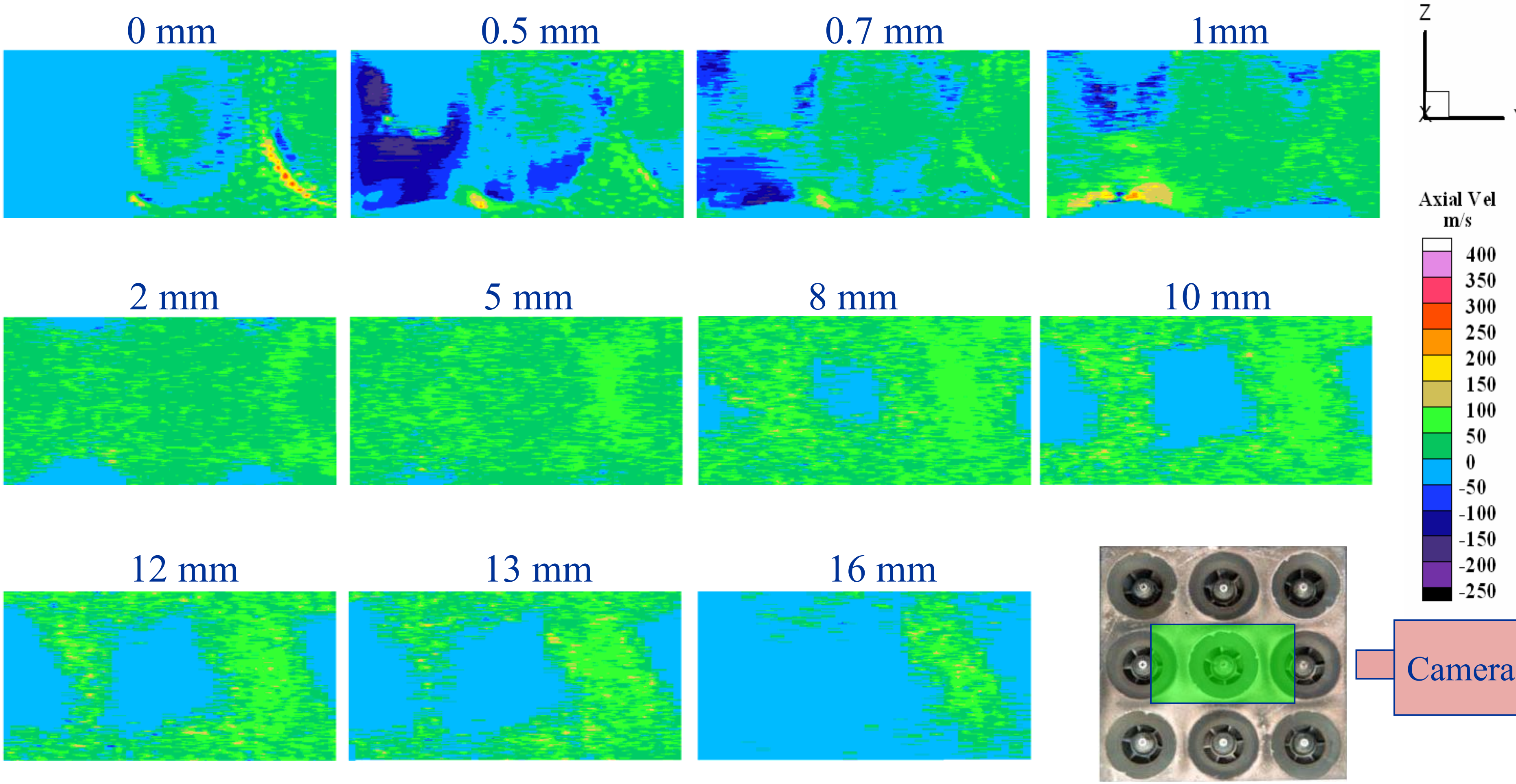
Inlet:
150 psia,
650°F,
$\phi = 0.45$



Within-plane velocity vectors near injection sites (top row) and between sites (bottom row)



Fuel axial velocity contours from 0 - 16 mm downstream from the injector exit plane. Inlet conditions: T_{in} = 617K, P_{in} = 1030 kPa, ϕ = 0.45

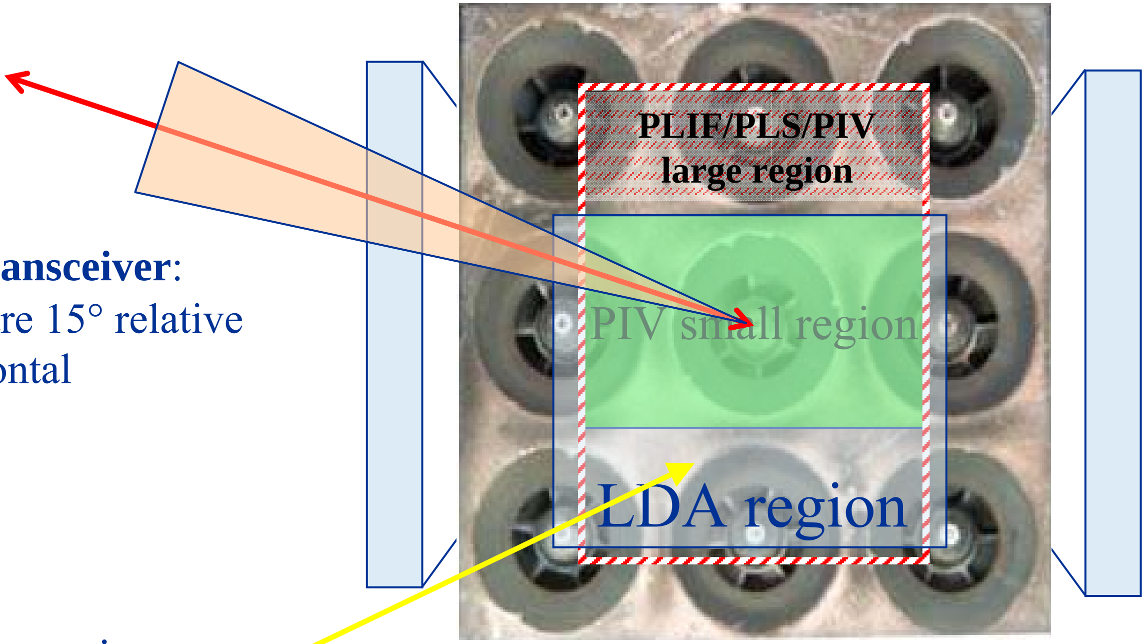


Results are preliminary

Planes nearest the injector exhibit symptoms of an opticaly thick field

Because the optical implementation is different, the PDA system accesses A somewhat different volume than the imaging work

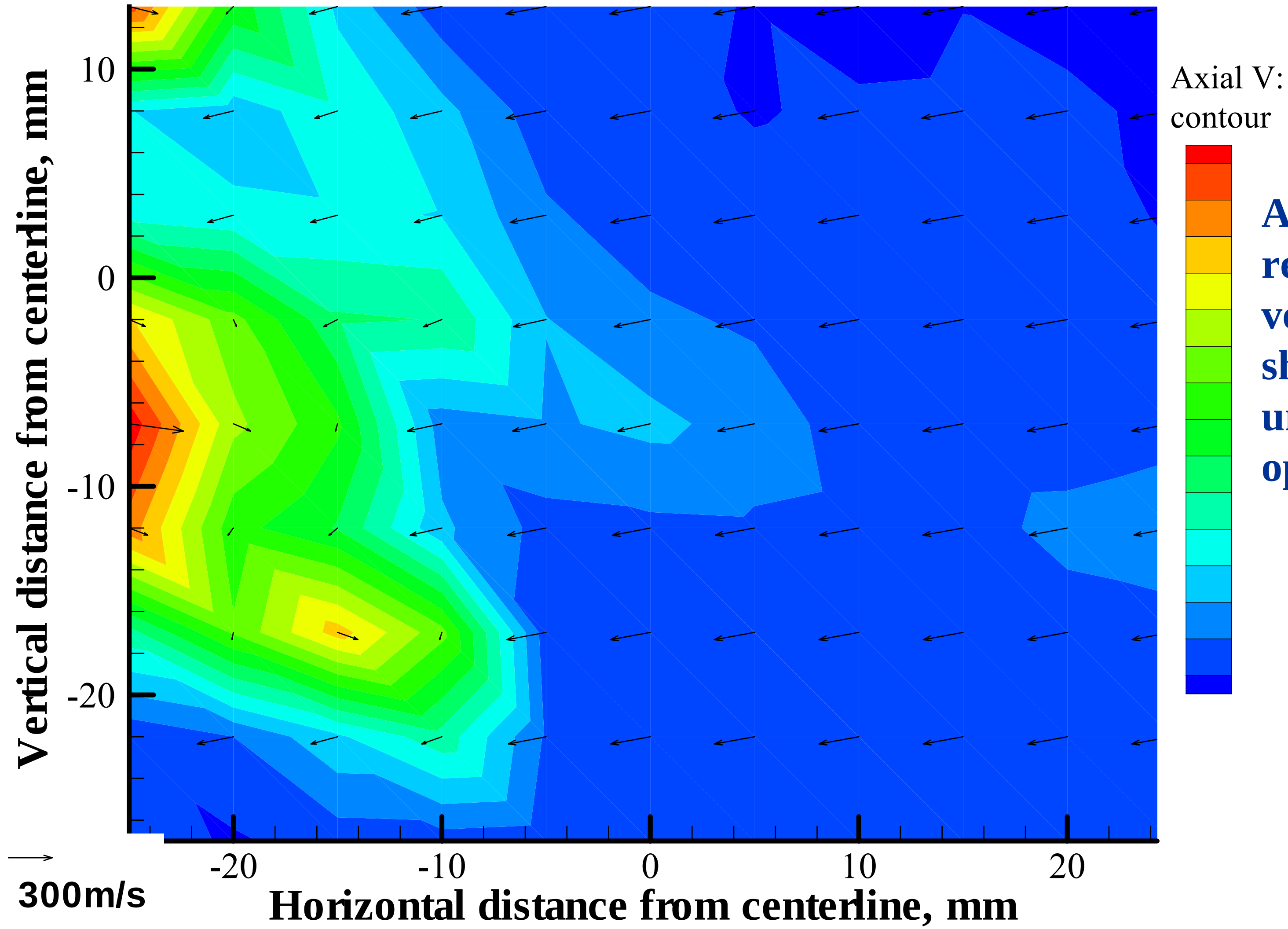
From transceiver:
Beams are 15° relative to horizontal



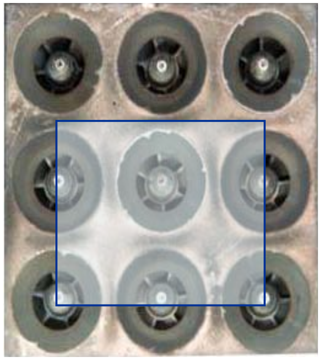
Approximate
PDA probe volume
(Note the shift wrt imaging probe volume)

Window full aperture = 1.5” (axial) x 2”

3-D Velocity distribution within axial plane 5-mm from exit.
Inlet conditions: T_{in} = 617K, P_{in} = 1030 kPa, ϕ = 0.45



As with the PIV result above, the velocity distribution shown here is uncorrected for optical thickness.



Summary

We performed the first of a series experiments to obtain baseline data for validating the NASA National Combustor Code using a 9-point LDI.

Species measurements

- PLIF images of fuel and OH were acquired and compared to similar PLS images from liquid fuel. Optical thickness/absorption are the primary issues to address.
- Image results show that this LDI atomizes and vaporizes fuel quickly. Chemiluminescence images are useful for determining the overall symmetry of the system.

Velocity meas—promising preliminary results despite tech issues

- Our first velocity/sizing measurements provide allow us to assess technique implementation determine how to improve. In general, we were successful
- PIV results show the presence of recirculation zones immediately downstream of the injector as predicted.
- A qualitative comparison of the axial air velocity from experiment and NCC code indicates a strong general agreement.
- Future velocity/turbulence/drop sizing, etc. measurements will need to address probable optical density/optical access issues, particularly for Phase Doppler